MODEL ATMOSPHERES:
Brown Dwarfs from the Stellar Perspective

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Abstract.

In this paper, we review the current theory of very low mass stars model atmospheres including the coolest known M dwarfs, M subdwarfs, and brown dwarfs, i.e. $T_{\text{eff}} \leq 5,000\,\text{K}$ and $-2.0 \leq [\text{M/H}] \leq +0.0$. We discuss ongoing efforts to incorporate molecular and grain opacities in cool stellar spectra, as well as the latest progress in deriving the effective temperature scale of M dwarfs. We also present the latest results of the models related to the search for brown dwarfs.

1. Very Low Mass Star models and the T_{eff} Scale

Very Low Mass stars (VLMs) with masses from about 0.3 $M_\odot$ to the hydrogen burning minimum mass (0.075 $M_\odot$, Baraffe et al. 1995) and young substellar brown dwarfs share similar atmospheric properties. Most of their photospheric hydrogen is locked in H_2 and most of the carbon in CO, with the excess oxygen forming important molecular absorbers such as TiO, VO, FeH and H_2O. They are subject to an efficient convective mixing often reaching the uppermost layers of their photosphere. Their energy distribution is governed by the millions of absorption lines of TiO and VO in the optical, and H_2O in the infrared, which leave **no** window of true continuum. But as brown dwarfs cool with age, they begin to differentiate themselves with the formation of methane (CH_4) in the infrared (Tsuji et al. 1995) at the expense of CO which bands begin to weaken in their spectra (Allard et al. 1996). Across the stellar-to-substellar boundary, clouds of e.g. corundum (Al_2O_3), perovskite ($CaTiO_3$), iron, enstatite ($MgSiO_3$), and forsterite (Mg_2SiO_4) may form, depleting the oxygen compounds and heavy elements and profoundly modifying the thermal structure and opacity of their photosphere (Sharp & Huebner 1990, Burrows et al. 1993, Fegley & Loggers 1996, Tsuji et al. 1996ab).

Because these processes also occur in the stellar regime where a greater census of cool dwarfs is currently available for study, a proper quantitative understanding of VLM stars near the hydrogen burning limit is a prerequisite to an understanding of the spectroscopic properties and parameters of brown dwarfs and jovian-type planets. Model atmospheres have been constructed by several investigators over recent years with the primary goals of:

1. Determining the effective temperature scale of M dwarf stars down to the substellar regime.

2. Identifying spectroscopic signatures of substellarity i.e. gravity indicators for young brown dwarfs, and spectral features distinctive of cooler evolved brown dwarfs.

3. Providing non-grey surface boundary to evolution calculations of VLMs and brown dwarfs leading to more consistent stellar models, accurate mass-luminosity relations and cooling tracks for these objects.

The computation of VLMs and brown dwarf model atmospheres requires a careful treatment of the convective mixing and the molecular opacities. The convection must currently be handled using the mixing length formalism while a variety of approximations have been used to handle the millions of molecular and atomic transitions that define the spectral distributions of VLMs and brown dwarfs. The most accurate of these methods is the so-called opacity sampling (OS) technique which consists in adding the contribution all transitions absorbing within a selected interval around each point of a pre-determined wavelength grid (typically ≈ 22000 points from 0.001 to 100 μm). When the detail of the list of transitions is lacking for a molecule as is the case for the important absorber VO, the Just Overlapping Line Approximation (JOLA) offers an alternative by approximating the band structure based on only a few molecular rotational constants. The straight-mean (SM) and K-coefficients techniques, which consist in averaging the opacities over fixed wavelength intervals chosen smaller than the resolution of typical observations, have also been used in modeling late-type dwarf atmospheres. Their main advantage is to save computing time during the calculation of the models, often at the expense of an accurate spectral resolution. The list of recent model atmospheres and the opacity technique they mostly rely upon is given in table 1.

Table 1.   Relevant Model Atmospheres

Authors	Grid	T_{eff} range (K)	Main Opacity Treatment
Kurucz 1992	Atlas12	$3500 - \ldots$	OS
Allard 1990	Base	$2000 - 3750$	SM+JOLA
Saumon et al. 1994	zero-metallicity	$1000 - 5000$	OS
Tsuji et al. 1995	grainless	$1000 - 2800$	JOLA
Brett 1995	MARCS	$2400 - 4000$	OS
Allard & Hauschildt 1995	Extended Base	$1500 - 4500$	SM
Tsuji et al. 1996	dusty	$1000 - 2800$	JOLA+Grains
Allard et al. 1996	NextGen	$900 - 9000$	OS
Allard et al. 1997b	NextGen-dusty	$900 - 3000$	OS+Grains
Marley et al. 1996		$\ldots - 1000$	K-coefficients

Because they mask emergent photospheric fluxes that would otherwise escape between absorption lines, the JOLA and SM approximations generally led to an excessive entrapment of heat in the atmosphere which yields systematically hotter model structures, and higher effective temperature (T_{eff}) estimates

Figure 1.   Current model-dependent effective temperature scales for cool stars down to the hydrogen burning limit. Triangles feature results from spectral synthesis of selected stars from the works of Kirkpatrick et al. (1993) and Leggett et al. (1996) as indicated. The new generation of OS models by Brett (1995b) and Allard et al. (1996), as interpolated onto theoretical isochrones by Chabrier et al. (1996), reproduce closely the independently-determined positions of the eclipsing M dwarf binary system CM Dra and YY Gem, and the empirical T_{eff} scale of Jones et al. (1994).

for individual stars. Allard et al. (1997) have reviewed in detail the results of brown dwarfs and VLM model atmosphere calculations with respect to the effective temperature scale of M dwarfs. We reproduce in Figure 1 the $T_{eff} - (V - I)$ relation of Allard et al. (1997) for the models listed in Table 1.

Two double-line spectroscopic and eclipsing M dwarf binary systems, CM Draconis and YY Geminorum, offer some guidance in the sub-solar mass regime and are reported in Figure 1 according to Habets & Heintze (1981). The use of an OS treatment of the main molecular opacities, in particular for TiO, appears to yield a break-through in the agreement of T_{eff} scales with these two M dwarfs binary system. The NextGen and MARCS models yield effective temperatures that are coincidentally in good agreement with those derived empirically from the H_2O opacity profile by Jones et al. (1994) [1]. Note, however, that the Atlas12 OS models suffer from an inaccurate TiO absorption profile and a complete lack of H_2O opacities, and are therefore clearly inadequate in the regime of VLM stars (i.e. below $T_{eff} \approx 4500$ K) where molecular opacities dominate the stellar spectra and atmospheric structures.

Some uncertainties on the metallicity of the CM Draconis system may soon disqualify the latter as a member of the disk main sequence (Viti et al. 1997). This stresses the importance of finding other low-mass eclipsing binary systems in the disk. These are hopefully soon to be provided by the 2MASS and DENIS surveys (see D. Kirkpatrick and X. Delfosse elsewhere in this volume). Much uncertainty remains, therefore, at the lowermost portion of the main sequence. The inclusion of grain formation (as discussed below) and more complete opacities of TiO promise a better understanding of the stars and brown dwarfs in the vicinity of the hydrogen burning limit (the location of which is roughly indicated in Figure 1 by the termination point of the Allard et al. 1996 model sequence), but still remain to be ascertained.

2.   The Infrared Colors of Brown Dwarfs

The DENIS and 2MASS infrared sky surveys will soon deliver large data bases of red dwarfs, brown dwarfs and perhaps extrasolar planets, which will necessi-

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[1] Note that a comparison to observed spectra reveals uncertainties of the order of 0.2 to 0.5 mag on the published *I* magnitudes of the latest-type M dwarfs Gl406, VB10 and LHS2924 analyzed by Jones et al. (1994) and reported on Figure 1.

Figure 2.   The observed infrared spectral distribution of the dM8e star VB10 as obtained at UKIRT by Jones et al. (1994) (bold full line) is compared to model spectra obtained using (from bottom to top): (i) the SM laboratory opacity profile of Ludwig (1971), (ii) the 20 million line list by Jørgensen et al. (1994), (iii) the preliminary ab initio line list of 6.2 million transitions by Miller & Tennyson (1994), and (iv) the latest ab initio list of 300 million lines by Partridge & Schwenke (1997). The models (shown as dotted lines) are all fully converged and normalized to the observation at 1.2 μm. Their parameters were determined from a fit to the optical stellar spectra (not shown) and are nearly the same in all four cases. Note that all 300 million lines of the Partridge & Schwenke list have been included in the model construction!

Figure 3.   The most recent models of late type dwarfs are compared to the photometric observations of field stars and brown dwarfs, and to Pleiades objects including the brown dwarfs PPl15, Teide1 and Calar3. Unresolved binarity is reflected in this diagram by a red excess in $J-K$. The red dwarfs newly discovered by DENIS (see X. Delfosse elsewhere in this volume) are also shown, although their photometry is still very uncertain at this point. The field brown dwarf Gliese 229B is off the scale to the blue in $J-K$ due to strong CH_4 absorption in the K bandpass. This diagram offers excellent diagnostics to identify brown dwarf candidates of the field (very red in either $J-K$ or $I-J$) or of the halo (very blue in both $I-J$ and $J-K$).

tate the best possible theoretical foundation. A proper understanding of their colors is essential in the search for brown dwarfs. Brown dwarfs and giant planets emit over 65 radiation in the infrared ($> 1.0\mu$m). Yet the main difficulties met by VLMs and brown dwarf modelers in recent years has been to reproduce adequately the infrared (1.4 to 2.5μm) spectral distribution of dwarfs with spectral types later than about M6. All models listed in the central part of table 1 underestimate the emergent flux, most as much as 0.5 mag at the K bandpass, despite the different opacity sources used by the authors. Allard et al. (1994, and subsequent publications) have explored water vapor opacity data from various sources. Figure 2 summarizes these results. Clearly, the water vapor opacity profile is quite uncertain and has varied with the degree of completeness and the assumptions used in the construction of the molecular model and its potential surface. The most recent and complete line list of Partridge & Schwenke succeeds for the first time in reproducing the 1.6 μm opacity minimum, in the H bandpass, well enough for the atomic NaI resonance line to finally emerge in the synthetic spectrum, matching the observed feature. However, it fails to provide an improvement in the K bandpass where the less complete list of Miller & Tennyson still yield the best match of the models to the observed spectra. The NextGen models of Allard et al. (1996) are computed using the Miller & Tennyson line list and are the only models to provide a match to the infrared colors of VLMs. This is shown in Figure 3 where the complete series of NextGen

models — as interpolated on the Baraffe et al. (1997) isochrones for 10 Gyrs and 120 Myrs and ranging from metallicities of [M/H]= -2.0 to 0.0 — are compared to the photometric field dwarfs' samples of Leggett (1992), Tinney et al. (1993), and Kirkpatrick et al. (1995). Other models series including those of Brett (1995) and the Extended grid of Allard & Hauschildt (1995, not shown) are distinctively bluer than the observed sequence, while the 10 Gyrs NextGen models of solar metallicity follow closely the empirical sequence[2] of Kirkpatrick & McCarthy (1994) until spectral types of M6 (i.e. $J - K \approx 0.85$). Beyond this point, all models fail to reproduce the bottom of the main sequence into the brown dwarf regime as defined by Gl406, VB10, BRI0021 and GD165B. The models catch up only at the much lower T_{eff} of the evolved brown dwarf Gliese 229B, i.e. 900-1000 K (Allard et al. 1996, Marley et al. 1996).

The cause of the model discrepancies at the stellar-to-brown dwarf boundary can only be one that affects the cooler models for Gliese 229B in a far lesser obvious extent. Since the infrared spectral distribution is sensitive to the mixing length, yet without allowing for an improved fit of VLMs spectra, Brett (1995a) suggested that the problem lie in the inadequacy of the mixing length formalism for treating the convective transport in an optically thin photospheric medium. These concerns may also be augmented by uncertainties about the extent of the overshooting phenomenon in VLMs (see F. D'Antona elsewhere in this volume). The convection zone recedes gradually below the photosphere as the mass (and T_{eff}) decreases along the isochrones. This implies that the lithium test of substellarity (Rebolo et al. 1992) — which relies on the assumption that the brown dwarf is still fully convective and mixing lithium from its core to its photospheric layers after 10^8 yrs of age — is inapplicable for objects cooler than $T_{eff} \leq 2200$ K. The presence of lithium in the spectra of a late-type ($\geq$M10) field dwarfs, if detected, could only reflect their initial abundances and **not** their substellar nature. The shrinking of the convection zone also allows a very good agreement between the models of Marley et al. (which includes adiabatic convection only for the optically thick layers of the atmosphere) and the models of Allard et al. (1996) (based on a more careful treatment of convection with the mixing length formalism) for the brown dwarf Gliese 229B (see Figure 5 of Allard et al. 1997). Yet the maximum radial extent of the convection zone occurs at around $T_{eff} = 3000$ K, while the discrepancy with the infrared observations increases steadily towards the bottom of the main sequence.

A more promising answer to the so called "infrared problem" may rather be found in the formation of dust grains in the very cool (typically $T_{layer} \approx T_{eff} - 1000$ K) upper layers of red and brown dwarf's atmospheres. Tsuji et al. (1996a) proposed, based on their results of including the effects of the formation and opacities of three grain species (Al_2O_3, Fe, and $MgSiO_3$) in their new "dusty" models, that the greenhouse heating of grain opacities, the resulting enhanced H_2O dissociation, and the infrared flux redistribution can explain the infrared spectra of cool M dwarfs. The formation of perovskite dust grains at the expense of TiO may also explain the observed saturation (and disappearance in

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[2]Note that this sequence was defined by stars selected from their optical spectroscopic properties. The somewhat erratic aspect of the sequence in this infrared diagram reflects uncertainties in the photometry and perhaps in the age of the selected stars.

GD165B and Gliese 229B) of the TiO bands in the optical spectra of late-type red dwarfs (see also Jones & Tsuji elsewhere in this volume). The implications of this result is far reaching. Field brown dwarf candidates such as BRI0021 and GD165B can be far cooler and less massive than previously suspected (see e.g. the NextGen-dusty model predictions in Figure1). If grains also form in the young Pleiades brown dwarfs PPl15, Teide1 and Calar3 ($T_{\rm eff} \approx 3000$, 2800, and 2700 K respectively), lithium abundances derived from grainless models and synthetic spectra such as those of Pavlenko et al. (1995, see also elsewhere in this volume) may be overestimated, and the masses attributed to these objects possibly underestimated. Evolution models of brown dwarfs, which are sensitive to the treatment of the atmospheres (Baraffe et al. 1995, Chabrier et al. 1996), and their predicted Mass-lithium abundance and Mass-Luminosity relations may also be affected.

And indeed, the temperatures and pressure conditions of the outer layers of red dwarfs are propice to the formation of dust grains as demonstrated years ago by Sharp & Huebner (1990) and Burrows et al. (1993). However it was not clear at the time if the inward radiation of an active chromosphere, or the efficient convective mixing from the interior, would heat up these upper photospheric layers and disable grain formation. Another concern is that, under the gravities prevailing in M dwarfs, gravitational settling may occur that would eliminate large grains and their opacities from the photospheres over relatively short time scales. These possibilities still need to be thoroughly investigated, but clearly, grain formation is a process that occurs in M dwarf and brown dwarf model atmosphere and it must included in such calculations.

In order to investigate which grains may form in the upper layers of M dwarfs, Allard et al. (1997b, in preparation) have modified the equation of states used in the NextGen models to include the detailed calculation of some 1000 liquids and crystals, using the free Gibbs energies compiled by Sharp & Huebner. Their results showed that, besides the three species considered by Tsuji et al., the M dwarfs atmosphere were rich in condensates with ZrO_2, $Ca_2Al_2SiO_7$, $Ca_2MgSi_2O_7$, $MgAl_2O_4$, Ti_2O_3, Ti_4O_7, $CaTiO_3$, and $CaSiO_3$ showing up in models as hot as $T_{\rm eff} = 2700-3000\,{\rm K}$ (i.e dM8-dM6)! The preliminary NextGen-dusty models have been computed using a continuous distribution of ellipsoid shapes and interstellar grain sizes (between 0.025 and 0.25 μm) for the treatment of the opacities of the Al_2O_3, Fe, $MgSiO_3$, and Mg_2SiO_4 dust grains (see Allard & Alexander elsewhere in this volume for computational details). This contrast with the assumption of spherical grains with 0.1 μm diameters in the dusty models Tsuji et al. Both model sets are shown in Figures 1 and 3. As can be seen, the dusty models of Tsuji et al. provide the correct tendency of the coolest models to get rapidly very red (as much as $J - K = 1.65$ for GD165B) with decreasing mass for a relatively fixed $I - J$ color. Those models are however systematically too red in $I - J$ by as much as 1 mag and do not reproduce even the most massive M dwarfs while over-predicting the effects of grains in Gliese 229B type brown dwarfs (Tsuji et al., 1996b), a problem which must be related to the use of the JOLA treatment of molecular opacities in these models (see section 1. above). The NextGen-dusty models, on the other hand, show the onset of grain formation effects by a progressive deviation from the grainless NextGen models for $J - K \geq 0.85$, bringing an improved agreement with the observed sequence in the region where the grainless NextGen models

deviate. Of course, much remains to be improved in the computation of models with dust grains. The size distribution of various grain species, in particular those of the perovskite $CaTiO_3$ which is responsible for the depletion of TiO from the optical spectra of late-type dwarfs (eg. GD165B, see D. Kirkpatrick elsewhere in this volume) and of corundum (Al_2O_3) which accounts for most of the grain opacities in current models, is unknown for the conditions prevailing in M dwarfs atmospheres. It is conceivable that grains form more efficiently in M dwarfs atmospheres than in the interstellar medium and therefore their opacities are larger than considered in the NextGen-dusty models. We may as well be missing a number of important contributors (e.g. ZrO_2) to the total grain opacities in the models. Further investigations including time dependent grain growth analysis will be required to determine the true contribution of dust grains to the infrared colors of red and brown dwarfs.

In the meanwhile, diagrams like that of Figure 3 may help in distinguishing interesting brown dwarfs candidates from large data banks of detected objects, and in obtaining an appreciation of the spectral sensitivity needed to detect new brown dwarfs. Models (Tsuji et al. 1995, Allard et al. 1996, Marley et al. 1996) and observations of Gliese 229B (see B. Oppenheimer elsewhere in this volume) have shown that methane bands at 1.7, 2.4 and 3.3 μm appear in the spectra of cool evolved brown dwarfs, and cause their $J - K$ colors to get progressively bluer with decreasing mass and as they cool over time. Yet their $I - J$ colors remain very red which allows to distinguish them from hotter low-mass stars, red shifted galaxies, red giant stars, and even from low metallicity brown dwarfs that are also blue due to pressure-induced H_2 opacities in the $H-$to$-K$ bandpasses. Fortunately, grain formation and uncertainties in molecular opacities are far reduced under low metallicity conditions ([M/H]< -0.5). Therefore, model atmospheres of metal-poor subdwarf stars and halo brown dwarfs are more reliable than their metal-rich counterparts at this point. This has been nicely demonstrated by Baraffe et al. (1997) who reproduced closely the main sequences of globular clusters ranging in metallicities from [M/H]$= -2.0$ to -1.0, as well as the sequence of the Monet et al. (1992) halo subdwarfs in color-magnitude diagrams (see G. Chabrier elsewhere in this volume). The colors of halo brown dwarfs as predicted by the NextGen models are therefore of quantitative quality await confrontation with the infrared colors of metal-poor subdwarfs from e.g. the Luyten catalog and the US Naval Observatory surveys. The sensitivity of the $I - J$ index to the chemical composition of the atmosphere (clearly illustrated by the NextGen model grid) allows to distinguish brown dwarf populations independently of an accurate knowledge of the parallaxes or distances involved. Even young brown dwarfs of lower gravity appear to form a distinct sequence at bluer $I - J$ (and redder $J - K$) values then that of their older field star counterparts as also evident from a comparison of the 10 Gyrs and 120 Myrs NextGen models. This gravity effect, and perhaps enhanced grain formation, may explain the scatter of spectroscopic properties observed among field dwarfs at the bottom of the main sequence (Kirkpatrick, this volume), as well as the systematic differences between Pleiades brown dwarfs and older field stars of same spectral type (i.e. same VO band strengths) noted by Martìn et al. (1996).

Gravity effects have also been found to affect the infrared spectra of cool evolved brown dwarfs such as Gliese 229B: Allard et al. (1996) reported a strong response of the 2.2 μm opacity minimum to gravity changes which allowed to

Figure 4. Predicted absolute fluxes of brown dwarfs at 50 pc as compared to the sensitivity of ground and space-based platforms which will be or are currently applied to the search for brown dwarfs and extrasolar planets. The latter are values reported for the 5 σ detection of a point source in 1 hr of integration, except for the three NICMOS cameras where the integration is limited to 40 minutes (Saumon et al. 1996). Models of both Allard et al. (1996) (full) and Marley et al. (1996) (dotted) are shown which simulate (i) a brown dwarf near the hydrogen burning limit (topmost spectrum: T_{eff} = 2000K), (ii) an evolved brown dwarf similar to Gliese 229B (central spectra: T_{eff} = 900K and 960K), and (iii) a brown dwarf closer to the deuterium burning limit (lowermost spectrum: T_{eff} = 500K). The corresponding black-body (dashed) are also shown for comparison.

restrain the mass of the brown dwarf [3]. The general spectral distributions of cool evolved brown dwarfs are well reproduced by current models despite the difference in their respective modeling techniques, and despite the uncertainties tied to grain formation and incomplete opacity data base for methane and ammonia. The models of Allard et al. (1996) and Marley et al. (1996) are compared in Figure 4 which also summarizes the predicted absolute fluxes that free-floating brown dwarfs would have at a distance of 50 pc. As can be seen, there is no clear cut distinction between brown dwarfs and planets; molecular bands most gradually form (dust, H_2O, CH_4 and NH_3) and recede (TiO, VO, FeH, and CO) from the stellar to the planetary regime as the atmospheres get cooler. They remain very bright in the IJK region, and become gradually redder in the near-infrared I to J bandpasses, which allows their detection from ground-based facilities. Layers of dust clouds in their upper atmospheres may increase the albedo of extrasolar planets and cool brown dwarfs sufficiently to reflect the light of a close-by parent star, becoming therefore resolvable in the optical where the clouds are densest but the parent star is however brightest. The peak of their intrinsic spectral energy distribution is located at 4.5 μm. At 5 μm, the hotter (younger or more massive) brown dwarfs and stars show strong CO bands which cause their flux to drop by nearly 0.5 dex relative to that at 4.5 μm. And between 4.5 and 10 μm, opacities of CH_4 (and H_2O in the hotter brown dwarfs) cause the flux to drop by 0.5 to 1.0 dex. Searches in the 4.5-5 μm region should therefore offer excellent possibilities of resolving brown dwarfs and EGPs in close binary systems, and to find free-floating brown dwarfs if space-telescope time allocations allow. The detection limits of current and planned ground-based and space-based telescopes Saumon et al. (1996) are also indicated in Figure 4 which show that brown dwarfs within 50 pc would be easily detected by SIRTF in the 4.5-5.0 μm region. The drop in sensitivity of the various instruments redwards of 10 μm implies, however, that brown dwarfs

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[3]Only within the error on the flux calibration of the observed spectra which are unfortunately large for this object.

and planets cooler than Gliese 299B have little chance to be detected in those redder bandpasses.

3. Conclusions

In these exciting times where discoveries of brown dwarfs are finally breaking through, model atmospheres are also rapidly becoming up to the task of interpreting the observations and deriving new search strategies. Uniform grids of dwarf stars and brown dwarfs model atmospheres exist that extend from the tip to the toes of the main sequence – and beyond: 9000K to 900K, logg= 3.0-6.0, and [M/H]= 0.0 to -2.0 for the NextGen models. These large model grids allowed the construction of consistent interior and evolution models for VLMs that yield unprecedent agreement with globular cluster main sequences observed to 0.1 M$_\odot$ with HST. They led to the derivation of the important mass-luminosity relation for halo brown dwarfs and so to the realization that brown dwarfs cannot make up a significant fraction of the halo missing mass.

The effective temperature scale of K to M type dwarfs with spectral types earlier than M6 is now unambiguously established, with only small uncertainties remaining from a possible incompleteness of existing TiO line lists. Grain formation has been identified as an important process in M dwarfs and brown dwarfs atmospheres which could explain the long-standing difficulties of the models to reproduce the spectral distribution of dwarfs later than about M6. The results of the models indicate that it may **not** longer be assumed that the convection zone extends to the photosphere of late-type red dwarfs and brown dwarfs, and that their photospheric lithium abundance reflect their core temperature and mass. The basic assumption supporting the lithium test of substellarity is only valid for young, hot brown dwarfs such as those found in the Pleiades cluster. Fortunately, if the lithium test cannot identify transition objects and brown dwarfs of the field, the OS molecular opacity treatment and grain formation have introduce new gravity (hence age) effects in the NextGen models that were not seen in the previous Extended models and that will potentially allow to separate younger transitional objects from field stars as readily as from their location in color-color diagrams. For this the colors of late-type red dwarfs need to be known with good accuracy i.e. better than about 0.05 magnitude, which we find is not the case of many known late M dwarfs such as Gl406, VB10, and especially LHS2924.

As cooler dwarfs are being discovered, spectral types are stretching far beyond the classical Morgan & Keenan scheme. The lack of TiO bands in the optical, and the emergeance of CH_4 opacities in the infrared in GD165B and Gl229B call for an extension of the MK system beyond M9 to another spectral class (see D. Kirkpatrick, this volume). While the spectral class should only reflect the effective temperatures and not necessarily the mass of the objects, perhaps a suitable class for these objects would nevertheless be "T dwarfs" as in reminescence of J.C. Tarter who introduced the term "brown dwarf" now commonly accepted to designate substellar dwarfs, and Takashi Tsuji who led the field of late dwarfs atmospheres since the early 1960's, first introduced methane as a spectral indicator of substellarity, and who is retiring soon. Another spectral class, perhaps "P", will then be needed for dwarfs cooler then the condensation

point of water vapor including planets. In any case, studies of the optical spectra of Gliese 229B, GD165B, the DENIS and 2MASS objects and other late-type dwarfs will soon allow to determine the stellar surface coverage of dust clouds if such are present, and to verify if intrinsic spectral-type variability afflict cool dusty dwarfs. Models will be the subject of further investigations relative to grain formation and its effect on late-type dwarfs until they can reproduce the lower main sequence and lead the way into the regime of cool brown dwarfs. Finally, if brown dwarfs are not abundant in the halo, they certainly are in the galactic disk and their study remains one that shall flourish as the census of the solar neighborhood continues and the gap between planets and stars fills in.

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